

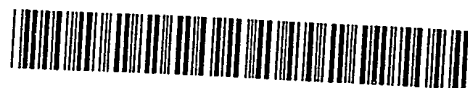
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(54) **Process for the formation of a collar oxide in a trench in a semiconductor substrate**

(57) A collar oxide is formed in a semiconductor substrate having (1) a partially full trench, (2) (i) a fill surface defined by fill material partially filling said trench, (ii) an upper surface outside of said trench, and (iii) a trench sidewall surface not covered by said fill material, and (3) a conformal oxide layer overlying said fill, upper, and sidewall surfaces, by selectively etching as follows:

- contacting the substrate with a mixture of hydrogen-containing fluorocarbon and an oxygen source under reactive ion etching conditions until at least a portion of the conformal oxide layer on the upper surface is removed, and
- contacting the substrate from step (a) with a mixture of a hydrogen-free fluorocarbon and a diluent gas under reactive ion etching conditions to further remove conformal oxide remaining on the fill surface and to overetch the upper and fill surfaces, whereby a substantial portion of conformal oxide remains on the side walls to form the collar oxide.

A further step (c) may be added after the overetching to remove any residual byproduct polymer deposits.

Such an approach is especially adapted for use in the manufacture of high aspect ratio trench capacitors for integrated circuits, since it provides reduced degradation of pad nitride layers and may be conducted without the use of CO gas.

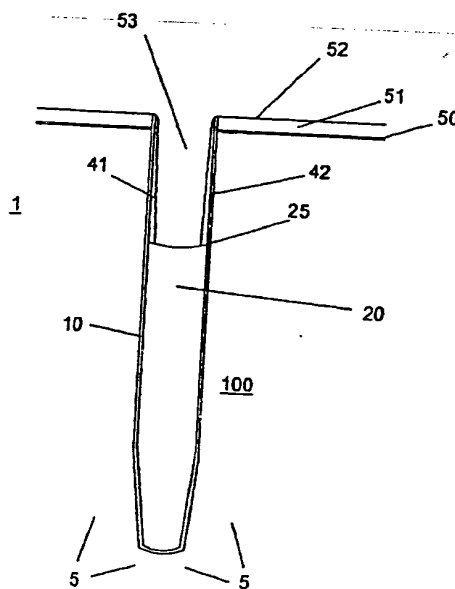


Fig. 5

[0001] The present invention relates to the formation of a collar oxide in a semiconductor substrate having a partially full trench.

[0002] Deep trench capacitors are used as components in dynamic random access memory (DRAM) devices and other integrated circuit devices. In the formation of integrated circuit devices on semiconductor wafers (chips), there is a continual desire to increase the number of devices per unit area of the chip surface. To meet this demand for increased device density, continual efforts are made to reduce the surface area taken up by device components such as capacitors. Trench capacitors having geometries involving high aspect ratios (depth normal to the principal wafer surface:width parallel to the principal wafer surface) allow more capacitors can be placed on the chip.

[0003] The general fabrication of trench capacitors and other trench-based component is well known. Typical processes involve etching of an initial trench into the substrate (or wafer, usually a silicon wafer). Prior to trench etching, one or more conformal dielectric material layers may be formed on the wafer surface. Typically, a conformal oxide dielectric layer will be closest to the semiconductor surface with a conformal nitride dielectric layer (so-called "pad nitride") overlying the oxide layer. The trench is then formed by etching through the pad dielectric layers and into the semiconductor substrate material. A region in the substrate at the bottom of the trench may be doped to provide a region of increased charge storage capacity which will become one plate of the capacitor. A thin node dielectric layer (high dielectric constant material) is formed as a conformal layer covering the trench surface. The trench is then filled with a doped polycrystalline silicon (polysilicon) or other charge storage material to form the other plate of the capacitor.

[0004] In order to enhance the reliability of the trench capacitor design by minimizing parasitic leakage at the trench sidewalls, a "collar" oxide may be formed about the upper inside surface of the trench. The formation of the collar oxide itself is a fairly complicated process. Typically, the top portion of the filled trench must be etched back leaving the dielectric layer along the upper portion of the trench sidewalls exposed. A conformal oxide layer (or typically a precursor thereof) is then deposited. The portion of the conformal oxide layer on the surface of the polysilicon (or other charge storage material) remaining in the partially filled trench is then selectively removed while leaving oxide about the upper sidewall of the trench to serve as a collar oxide. In the process of removing the conformal oxide from the polysilicon surface, the portion of this conformal oxide layer outside the trench (i.e. overlying the pad nitride) is also removed. The unfilled portion of the trench is then refilled with polysilicon to complete the formation of the capacitor plate with the collar oxide residing near the

upper end of the trench.

[0005] This selective removal of the conformal oxide is a key step in trench capacitor fabrication. If the oxide is not completely removed from the polysilicon (or other fill material) surface where the trench is to be refilled, the performance of the capacitor may be compromised due to poor electrical connection between the polysilicon material deep in the trench and the polysilicon material deposited on trench refilling (i.e. in the portion of the trench having the collar oxide along the trench walls). Further, the selective removal of the conformal oxide must not adversely affect the underlying node dielectric layer, the dielectric pad dielectric layer or other features which are present on the substrate outside the trench. Protection of the pad nitride layer near the top of the trench is especially important since it is typically used as an etch stop during the subsequent processing of the substrate. These process demands are made more difficult by the continued move to smaller dimension/higher aspect ratio geometries (e.g. 20 or higher).

[0006] Typically reactive ion etching or other dry etching processes have been used to achieve the selective removal of the conformal oxide. These processes have exhibited problems of slow etch rate (long process time), formation of undesired by-products/deposits, required use of problematic gases such as CO₂ and/or lack of reliability, resulting in low yields or need for very tight control of process parameters. Thus, there remains a need for improved processes for conformal oxide etching, especially for use in the fabrication of trench capacitors.

[0007] Accordingly, the invention provides a method of forming a collar oxide in a semiconductor substrate having a partially full trench; a fill surface defined by fill material partially filling said trench, an upper surface outside said trench, and a trench sidewall surface not covered by said fill material; and a conformal oxide layer overlying said fill, upper, and sidewall surfaces, said method comprising selectively etching said conformal oxide by the steps of:

- (a) contacting said substrate with a mixture of hydrogen-containing fluorocarbon and an oxygen source gas under reactive ion etching conditions until at least a portion of conformal oxide on said upper surface is removed; and
- (b) contacting the substrate after step (a) with a mixture of a hydrogen-free fluorocarbon and a diluent gas under reactive ion etching conditions to further remove conformal oxide remaining on said fill surface and to overetch said upper and fill surfaces, whereby a substantial portion of said conformal oxide remains on said sidewall surface to form said collar oxide.

[0008] In a preferred embodiment, the method further comprises the step of: (c) contacting said etched substrate from step (b) with a gas containing at least one

component selected from the group consisting of O_2 , NE_3 , and CF_4 to remove any residual polymer deposited on said surfaces during steps (a) or (b), typically at a pressure of about 25-300 millitorr and a power of about 50-300 watts. Subsequently, the trench may be filled with an additional amount of said fill material.

[0009] Also, in a preferred embodiment, at least a portion of said upper surface comprises a nitride composition such as silicon nitride and silicon oxynitride, and said etching in step (a) is conducted until said nitride composition is exposed.

[0010] With regard to step (a), it is preferred that said mixture comprises about 40-100 parts by volume of said hydrogen-containing fluorocarbon (for example, trifluoromethane), and about 2-15 parts by volume of said oxygen source gas, and that said reactive ion etching conditions include an operating pressure of about 50-150 millitorr and a power of about 200-500 watts. A hydrogen-free fluorocarbon may also be included in the mixture.

[0011] With regard to step (b), it is preferred that said mixture comprises about 3-20 parts by volume of said hydrogen-free fluorocarbon and about 50-300 parts by volume of said diluent gas (for example, Ar, He, Xe, N_2 , and mixtures thereof), and that said reactive ion etching conditions include an operating pressure of about 25-200 millitorr and a power of about 500-1200 watts. It is further preferred that the hydrogen-free fluorocarbon has a C/F atomic ratio greater than at least 0.25, more preferably at least 0.5, for example, C_4F_8 .

[0012] In the preferred embodiment, step (b) is conducted for about 0.1-2 times the amount of time taken to conduct step (a). Also in the preferred embodiment, the conformal oxide layer comprises silica and the material partially filling said trench is selected from the group consisting of polysilicon and doped polysilicon. It is further preferred that the sidewall surface is coated with a high dielectric constant material layer prior to application of said conformal oxide.

[0013] Thus an improved method for selective etching of conformal oxide layers is provided herein. This can be used for forming a collar oxide in a trench in a semiconductor substrate to provide improved integrity of pad dielectric layers resulting in enhanced structural and operational reliability of the resulting devices. The method is especially useful in the manufacture of high aspect ratio trench capacitors for integrated circuits and other processes involving high aspect ratio oxide etching in the absence of resist.

[0014] In the method for forming a collar oxide in a trench in a semiconductor substrate, the conformal oxide is preferably completely removed from the upper surface in step (a), and a further step (c) may be added after the overetching to remove any residual byproduct polymer deposits. The method may be practiced without the use of gases such as CO. The trench having the formed collar oxide may then be further filled with an additional portion of the fill material and/or may be sub-

jected to other processing steps for forming an electrically functioning structure such as a capacitor. Doped polysilicon is a preferred fill material. The approach described herein is especially useful where some or all of the upper surface of the substrate comprises a pad dielectric layer such as silicon nitride, and is also especially useful in the manufacture of trench devices having a high trench (depth to width) aspect ratio.

[0015] Thus an improved method is provided for the selective removal of portions of conformal oxide layers which is particularly suited to the formation of collar oxides for semiconductor substrate trenches such as those used to form trench capacitors and for other high aspect ratio etching applications.

[0016] A preferred embodiment of the invention will now be described in detail by way of example only with reference to the following drawings:

Figure 1 is a schematic cross section view of a high aspect ratio trench after formation of thin node dielectric layer and filling with charge storage fill material and partial etch back of the fill material;

Figure 2 is a schematic cross section view of the trench of Figure 1 with the application of a conformal oxide layer;

Figure 3 is a schematic cross section view of the trench of Figure 2 after removal of the conformal oxide layer from the upper surface of the substrate; Figure 4 is a schematic cross section view of the trench of Figure 3 after further removal of the conformal oxide layer from the fill surface and deposition of residual byproducts;

Figure 5 is a schematic cross section view of the trench of Figure 4 after further removal of the residual byproducts.

Figure 6 is a schematic cross section view of the trench of Figure 5 after filling with additional fill material.

[0017] The invention will be described in relation to the formation of a trench structure. The basic structure of the trench capacitor is schematically illustrated in the Figures (it should be understood that none of these drawings is necessarily to scale). It will be appreciated that the invention is not limited to any specific method of trench formation. General techniques for forming trench capacitors having collar oxide features are known in the art. See for example the methods disclosed in US Patents 4,794,434; 5,283,453; 5,434,109; 5,656,535; and 5,677,219, the disclosures of which are incorporated herein by reference.

[0018] A typical method of trench formation method will now be described, referring initially to Figure 1, which depicts part of the fabrication of a trench capacitor. This process involves first coating the wafer or substrate 1 with one or more conformal pad dielectric layers, usually an oxide layer 50 followed by a nitride layer 51. A trench 100 is then etched into the substrate

1. The trench etching is usually performed by applying a TEOS (tetraethyl orthosilicate) hard mask layer (not shown) over the uppermost pad dielectric layer. A patterned photoresist layer (not shown) is then formed over the hard mask layer. The hard mask is then patterned by selectively etching. Then, the remaining photoresist layer is typically stripped and the trench is formed by anisotropic etching through the pad dielectric layers 50, 51 and a portion of the semiconductor substrate 1 to form the desired trench 100. The hard mask oxide is then removed. Regions 5 in the substrate near the wall of the trench may be doped to provide a region of increased charge storage capacity which will become one plate of the capacitor. A thin node dielectric layer 10 is formed as a conformal layer covering the trench surface. After formation of the node dielectric 10, the trench 100 is then filled with a charge storage material 20 (typically a doped polysilicon) which is then etched back leaving a fill surface 25.

[0019] To form the collar oxide, a conformal oxide layer 40 (Fig. 2) or typically a precursor thereof is then deposited over the trench, thus covering the fill surface 25, the upper sidewalls 42 and the top surface 52 (e.g. the surface of uppermost pad dielectric 51). The portion of the conformal oxide layer on the fill surface 25 and the top surface must then be selectively removed while leaving oxide about the upper sidewall of the trench to serve as a collar oxide. The conformal oxide must also be removed from the dielectric features 50 on the substrate surface outside the trench. The upper portion 53 of the trench is then refilled with additional charge storage material (Fig. 6) to complete the formation of the capacitor plate with the collar oxide 41 residing near the upper end of the trench.

[0020] Thus if we start with a semiconductor substrate having (1) a partially-filled (e.g. filled and etched back) trench, (2) (i) fill surface defined by fill material partially filling the trench, (ii) upper surface outside of the trench, and (iii) trench sidewall surface not covered by the fill material, and (3) a conformal oxide layer overlying the fill, upper, and sidewall surfaces, the question is how best to remove a portion of the conformal oxide by selective etching.

[0021] As will be described in more detail below, this can be accomplished in accordance with the present invention by:

(a) contacting the substrate with a mixture of hydrogen-containing fluorocarbon and an oxygen source under reactive ion etching conditions until at least a portion of the conformal oxide layer on the upper surface is removed, and

(b) contacting the substrate from step (a) with a mixture of a hydrogen-free fluorocarbon and a diluent gas under reactive ion etching conditions to further remove conformal oxide remaining on the fill surface and to overetch the upper and fill surfaces, whereby a substantial portion of conformal oxide

remains on the sidewall surfaces to form the collar oxide.

[0022] Preferably, the conformal oxide is completely removed from the upper surface in step (a). A further step (c) may be added after the overetching to remove any residual byproduct polymer deposits.

[0023] Describing now a particularly preferred process in detail, the starting structure having a conformal oxide layer over a partially filled trench may be formed by any conventional means such as those described in the above mentioned US patents. The conformal oxide is formed using a tetraethylorthosilicate (TEOS) chemical vapor deposition (CVD) technique which results in a conformal SiO₂ layer (although any collar oxide composition may be used).

[0024] The upper surface of the substrate has one or more pad dielectric layers applied prior to trench formation which underlie the conformal oxide coating deposited over the partially full trench. The uppermost pad dielectric is a nitride such as silicon nitride or silicon oxynitride. Where the structure is to be used as a capacitor, the material partially filling the trench (and thereby forming the fill surface) is a material capable of holding and discharging electrical charge. Preferred fill materials are doped polysilicons (polycrystalline silicon) such as are commonly used in the formation of trench capacitors.

[0025] The trench may have any desired geometry or aspect ratio, dimensions or layer thicknesses, although the approach described herein is especially useful for trench capacitors having an aspect ratio (depth:width) of at least about 5, more particularly at least about 20, wherein the trench depth is measured from the semiconductor surface at the trench entrance in the direction normal to the semiconductor surface, and the trench width is measured as the maximum width in the trench in a direction parallel to the semiconductor surface.

[0026] Both etching steps (a) and (b) above involve the removal of a portion of the conformal oxide applied over a partially full trench. In step (a), the substrate is contacted with a mixture of hydrogen-containing fluorocarbon and an oxygen source under reactive ion etching conditions until at least a portion of the conformal oxide layer on the upper surface is removed.

[0027] In the preferred embodiment, the hydrogen-containing fluorocarbon gas consists of C, H and F atoms; preferably the hydrogen-containing fluorocarbon gas is selected from the group consisting of CHF₃, CH₂F₂, CH₃F and mixtures thereof. Most preferably, the hydrogen-containing fluorocarbon gas consists essentially of CHF₃. The oxygen source is selected from the group consisting of diatomic oxygen (O₂), oxygen-containing reducing gases such as CO₂, CO, and mixtures thereof. A diluent gas such as helium or argon may also be included. O₂ is the preferred oxygen source gas from the point of minimizing byproduct polymer formation and other adverse effects. The flow of the hydrogen-

containing fluorocarbon is about 40-100 sccm, preferably about 60-80 sccm. The flow of the oxygen source gas is about 2-15 sccm. Preferably, the use of CO gas is avoided.

[0028] The reactive ion etching conditions in step (a) include about 50-150 millitorr operating pressure, about 200-500 watts power, and about 0-90 gauss magnetic field. In some circumstances, it may also be desirable to add a minor flow of a hydrogen-free fluorocarbon such as C_4F_8 or CF_4 to the overall gas mix. The total flow of such hydrogen-free fluorocarbons in step (a) is about 2-20 sccm.

[0029] Chemical detection means are used to monitor the evolution of reaction products associated with the reaction of the upper surface layer underlying the conformal oxide layer. Where the upper surface comprises a pad nitride layer, chemical detection means may be used to monitor the evolution of nitrogen-containing reaction products (e.g. CN or Si_xN_y species) or other reaction products (e.g. Si_xF_y). Typically, when the conformal oxide completely covers the pad nitride, little or no nitrogen-containing reaction products are detected. On exposure of the pad nitride, the evolution of nitrogen-containing reaction products increases until it reaches a steady state concentration which generally corresponds to complete or nearly complete exposure of the pad nitride (i.e. the nitride surface area exposed for reaction approaches a constant).

[0030] Etching step (a) is carried out at least until a substantial amount of the conformal oxide layer has been removed from the upper surface (e.g. the pad nitride surface), preferably, at least until the evolution of reaction products associated with reaction of the upper surface (typically nitrogen-containing reaction products) occurs. Most preferably, etching step (a) is continued at least until this steady state concentration from the evolution of upper surface reaction products is first reached. This state is schematically illustrated in Figure 3 where conformal oxide 40 is no longer present above pad dielectric 51. Step (a) may be continued for some time (over-etch) after the steady state is first reached, but, to minimize erosion of the pad nitride, etching step (a) is preferably not carried out for too much time after first reaching the steady state. On the other hand, the switchover to step (b) is not done before a substantial portion of the conformal oxide has been removed from the upper surface, otherwise excessive undesired byproducts may be formed.

[0031] In step (b), the substrate from step (a) is contacted with a mixture of a hydrogen-free fluorocarbon and a diluent gas under reactive ion etching conditions to further remove conformal oxide remaining on the fill surface 25 and to overetch the upper and fill surfaces, whereby a substantial portion of conformal oxide remains on the sidewalls to form the collar oxide. The etchant mixture in step (b) preferably etches oxide very selectively without substantial degradation of the pad nitride or the trench fill material. As shown in Figure 4,

the etching of the oxide at the fill surface 25 is preferably highly anisotropic such that the profile of the conformal oxide 41 on the sidewall is projected directly down to the fill surface 25 and a substantially clean (i.e. conformal oxide-free) fill surface away from the sidewall conformal oxide 41 is obtained. In step (b), polymer byproducts may be deposited on the etched surfaces. These byproducts are shown generally as layer 70.

[0032] In the preferred embodiment, the hydrogen-free fluorocarbon is a fluorocarbon having a C:F atomic ratio of at least about 0.33, preferably at least about 0.5. Examples of preferred hydrogen-free fluorocarbons are disclosed in US Patent 5,338,399, the disclosure of which is incorporated herein by reference. Cyclic C_4F_8 is most preferred. The diluent may be any gas which does not have an adverse affect on the performance of the hydrogen-free fluorocarbon or the overall etching operation. Preferred diluents are noble gases such as Ar, He, and Xe, most preferably Ar. Other gases such as N_2 can also be used as a diluent. The flow of hydrogen-free fluorocarbon is preferably about 3-20 sccm. The flow of diluent gas is about 50-300 sccm. The gas mixture used in step (b) may contain a minor amount of other fluorine compound gas such as hydrogen-containing fluorocarbons or SF_6 , however, the molar ratio (or volume ratio at constant pressure) of hydrogen-free fluorocarbon to hydrogen-containing fluorocarbon is greater in step (b) than in step (a). Preferably, the use of CO gas is avoided. The reactive ion etching conditions in step (b) include about 25-200 millitorr operating pressure, about 500-1200 watts power, and about 0-90 gauss magnetic field. The step (b) etching process is conducted until the oxide is completely removed at fill surface 25 with the exception of the vertical projection (i.e. substantially normal to the fill surface) of sidewall oxide 41 as shown in Figure 4. Preferably, step (b) is conducted for not more than twice the time used in step (a), more preferably for about 50-100% of the time used in step (a).

[0033] Typically, etching step (b) will result in the formation of a polymer byproduct deposit 70 (Figure 4) on the substrate. The deposited polymer is removed in a cleaning step (c) before further processing of the substrate. This removal results in a clean surface as schematically illustrated in Figure 5. The cleaning step (c) involves contacting the substrate from step (b) with a gas containing at least one component adapted to facilitate removal of the polymer byproduct, preferably a gas component selected from the group consisting of NF_3 , CF_4 , O_2 , or mixtures thereof. The gas component is most preferably CF_4 . For NF_3 , the flow rate is about 2-100 sccm, preferably about 10-100 sccm. For CF_4 , the flow rate is about 10-200 sccm. For O_2 , the flow rate is about 10-200 sccm. Preferably, the use of CO gas is avoided. Diluent gases such as Ar, He, N_2 , or Xe may be used in combination with the above mentioned gases. The cleaning is conducted under conditions which preferably include about 25-300 millitorr operat-

ing pressure, about 50-300 watts power, and about 0-90 gauss magnetic field. The cleaning step is preferably performed for about 1-100 seconds.

[0034] Once the cleaned, etched structure is obtained with the desired collar oxide and clean fill surface. The trench may now be refilled with an additional amount 30 of charge storage material as shown in Figure 6. Such filling techniques are well known in the art. Alternatively, the structure may be subjected to other manufacturing processes as may be desired.

[0035] It will be appreciated that the etching processes described above may be performed in any conventional etching apparatus normally used for reactive ion etching of oxides. A preferred etching apparatus is model AME MXP+ sold by Applied Materials Inc.

Claims

1. A method of forming a collar oxide (41) in a semiconductor substrate (1) having a partially full trench (100); a fill surface (25) defined by fill material partially filling said trench, an upper surface (52) outside said trench, and a trench sidewall surface (42) not covered by said fill material; and a conformal oxide layer (40) overlying said fill, upper, and sidewall surfaces, said method comprising selectively etching said conformal oxide by the steps of:
 - (a) contacting said substrate with a mixture of hydrogen-containing fluorocarbon and an oxygen source gas under reactive ion etching conditions until at least a portion of conformal oxide on said upper surface is removed; and
 - (b) contacting the substrate after step (a) with a mixture of a hydrogen-free fluorocarbon and a diluent gas under reactive ion etching conditions to further remove conformal oxide remaining on said fill surface and to overetch said upper and fill surfaces, whereby a substantial portion of said conformal oxide remains on said sidewall surface to form said collar oxide.
2. The method of claim 1, further comprising the step of: (c) contacting said etched substrate from step (b) with a gas containing at least one component selected from the group consisting of O₂, NF₃, and CF₄ to remove any residual polymer deposited on said surfaces during steps (a) or (b).
3. The method of claim 2 wherein said contacting in step (c) is performed at a pressure of about 25-300 millitorr and a power of about 50-300 watts.
4. The method of claim 2 or 3 wherein said method further comprises filling the trench after step (c) with an additional amount of said fill material.
5. The method of any preceding claim wherein at least a portion of said upper surface comprises a nitride composition and said etching in step (a) is conducted until said nitride composition is exposed.
6. The method of claim 5 wherein said nitride composition comprises a nitride selected from silicon nitride and silicon oxynitride.
7. The method of any preceding claim wherein said mixture in step (a) further comprises a hydrogen-free fluorocarbon.
8. The method of any preceding claim wherein said mixture in step (a) comprises about 40-100 parts by volume of said hydrogen-containing fluorocarbon and about 2-15 parts by volume of said oxygen source gas.
9. The method of any preceding claim wherein said reactive ion etching conditions in step (a) include an operating pressure of about 50-150 millitorr and a power of about 200-500 watts.
10. The method of any preceding claim wherein said hydrogen-containing fluorocarbon is trifluoromethane.
11. The method of any preceding claim wherein said mixture in step (b) comprises about 3-20 parts by volume of said hydrogen-free fluorocarbon and about 50-300 parts by volume of said diluent gas.
12. The method of any preceding claim wherein said diluent gas is selected from the group consisting of Ar, He, Xe, N₂, and mixtures thereof.
13. The method of any preceding claim wherein said reactive ion etching conditions in step (b) include an operating pressure of about 25-200 millitorr and a power of about 500-1200 watts.
14. The method of any preceding claim wherein said mixture in step (b) comprises a hydrogen-free fluorocarbon having a C/F atomic ratio greater than 0.25.
15. The method of claim 14 wherein said mixture in step (b) comprises a hydrogen-free fluorocarbon having a C/F atomic ratio at least about 0.5.
16. The method of claim 15 wherein said hydrogen-free fluorocarbon is C₄F₈.
17. The method of any preceding claim wherein step (b) is conducted for about 0.1-2 times the amount of time taken to conduct step (a).

18. The method of any preceding claim wherein said material partially filling said trench is selected from the group consisting of polysilicon and doped polysilicon.
19. The method of any preceding claim wherein said sidewall surface is coated with a high dielectric constant material (10) layer prior to application of said conformal oxide.
20. The method of any preceding claim wherein said conformal oxide layer comprises silica.

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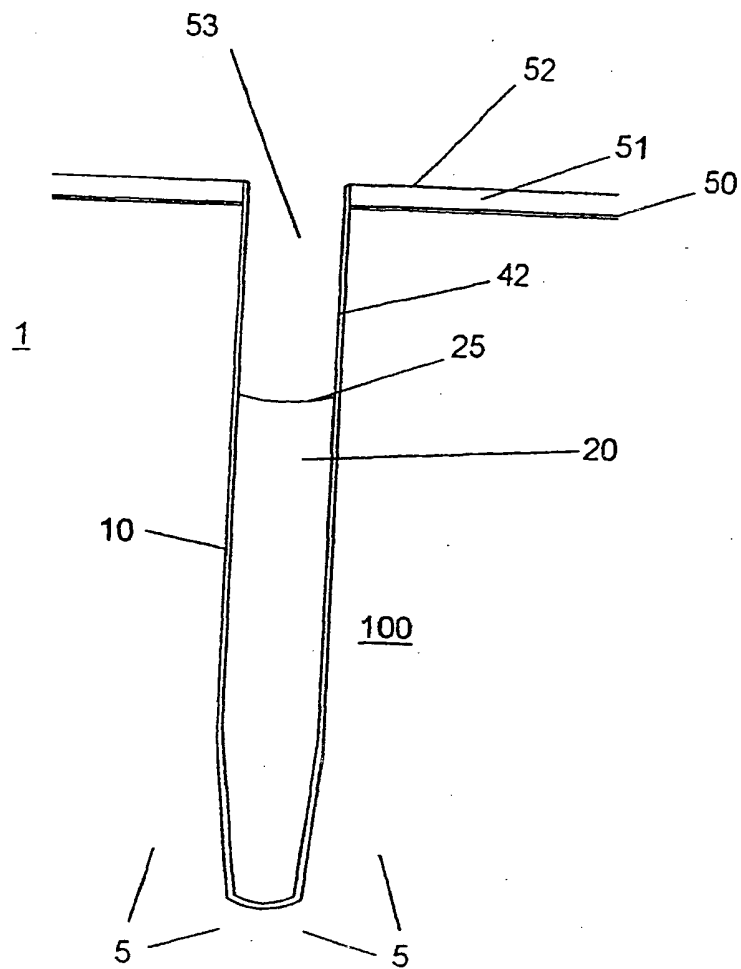


Fig. 1

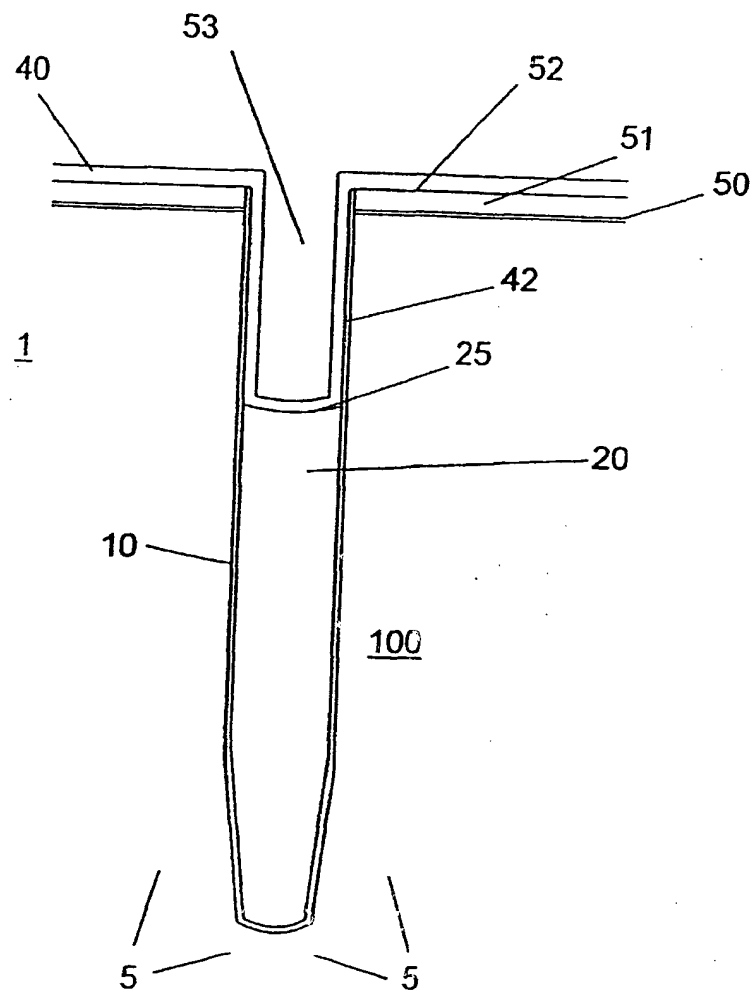


Fig. 2

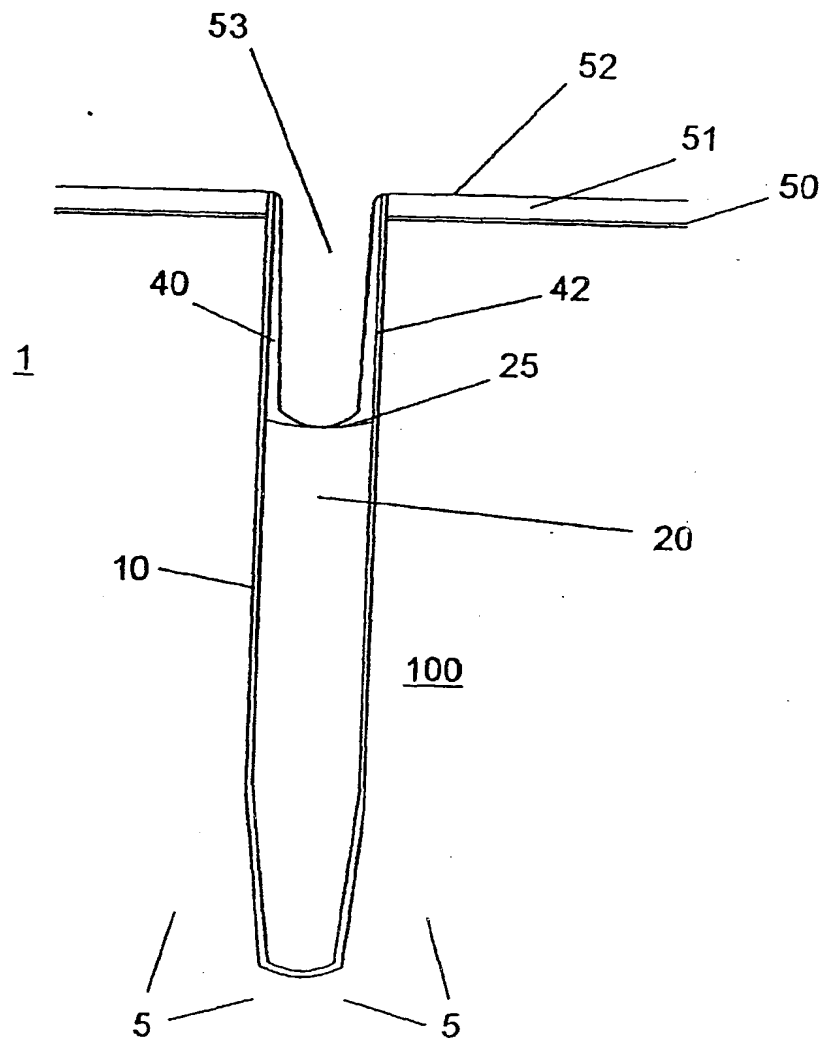


Fig. 3

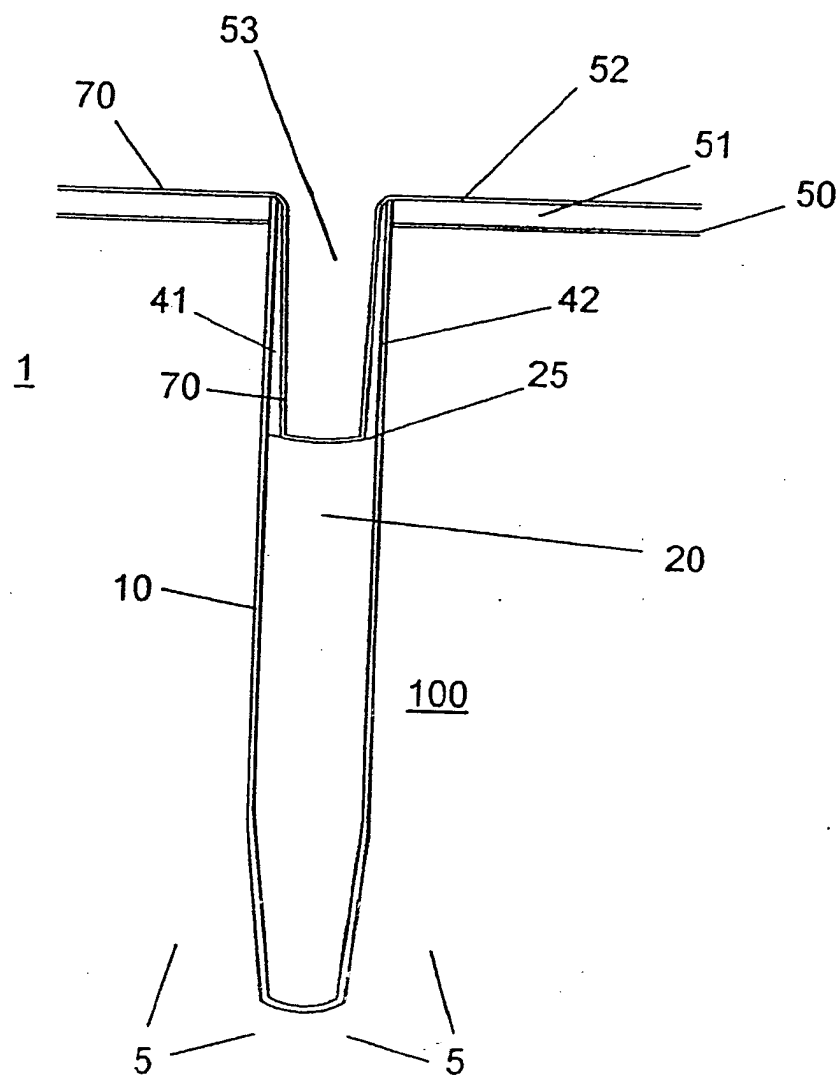


Fig. 4

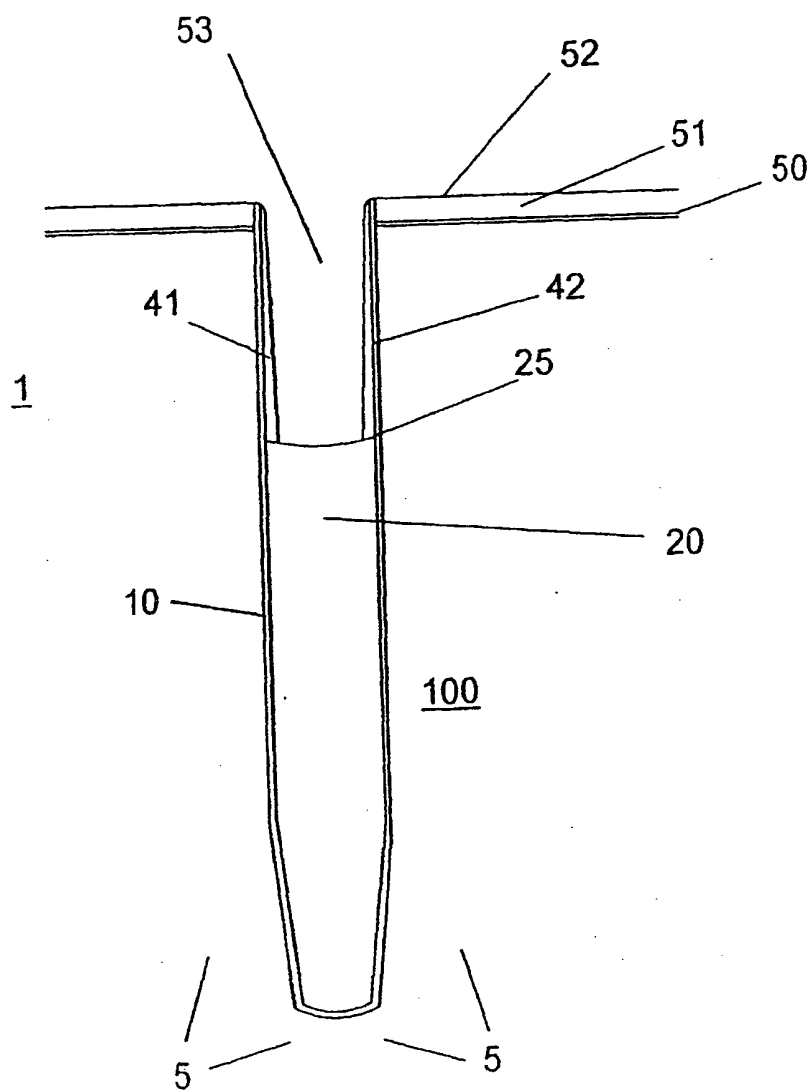


Fig. 5

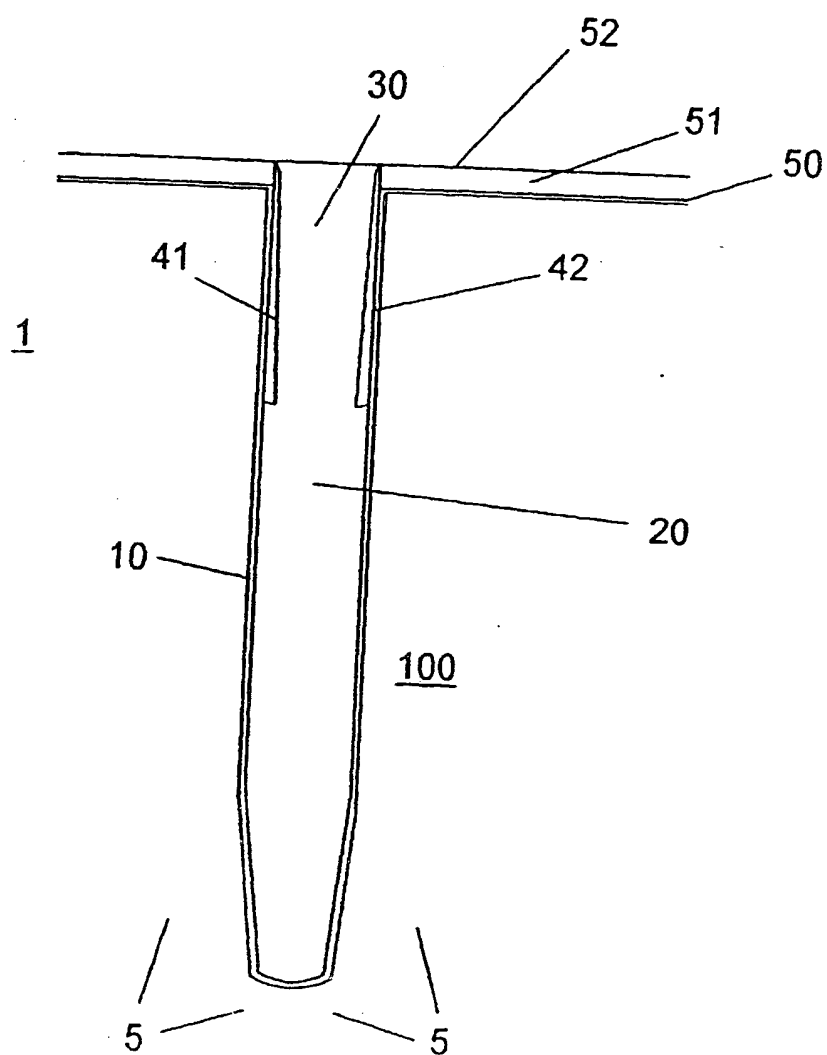


Fig. 6